

Neutrino Factory Designs and R&D

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European, Japanese, and US Neutrino Factory designs are presented. The main R&D issues, and the associated R&D programs, are discussed.

1. Introduction

The development of a very intense muon source capable of producing a millimole of muons per year would enable a Neutrino Factory [1], and perhaps eventually a Muon Collider [2], to be built. In the last two years Neutrino Factory physics studies [3] have mapped out an exciting Neutrino Factory physics program. In addition, Neutrino Factory feasibility studies [4–6] have yielded designs that appear to be “realistic” provided the performance parameters for the critical components can be achieved. Some of the key components will need a vigorous R&D program to meet the requirements. Neutrino Factory R&D activities in Europe [7], Japan [6,8], and the US [9] have resulted in three promising variants of the basic Neutrino Factory design. In the following the various Neutrino Factory schemes are briefly described. The main R&D issues and the ongoing R&D programs are summarized.

2. Neutrino Factory Schemes

In all of the present Neutrino Factory schemes an intense multi-GeV proton source is used to make low energy charged pions which are confined within a large acceptance decay channel. The daughter muons produced from π^\pm decays

are also confined within the channel. However, the muons occupy a large phase-space volume which presents the main challenge in designing a Neutrino Factory. In the US and European designs the strategy is to first reduce the energy spread of the muons by manipulating the longitudinal phase-space they occupy using a technique called “phase rotation”. The transverse phase-space occupied by the muons is then reduced using “ionization cooling [10]”. After phase rotation and ionization cooling the resulting muon phase space fits within the acceptance of a normal type of accelerator. In the Japanese scheme an alternative strategy is pursued in which the large muon phase-space is accommodated using so called FFAG’s, which are very large acceptance accelerators. Finally, in all three schemes the muons are accelerated to the desired final energy (typically in the range from 20 - 50 GeV), and injected into a storage ring with either two or three long straight sections. Muons decaying within the straight sections produce intense neutrino beams. If the straight section points downwards, the resulting beam is sufficiently intense to produce thousands of neutrino interactions per year in a reasonably sized detector on the other side of the Earth [1] !

2.1. US Scheme

In the last 2 years there have been two Neutrino Factory “Feasibility” Studies [4,5] in the US. Within these studies engineering designs have been developed and detailed simulations performed for each piece of the Neutrino Factory complex. Study I was initiated by the Fermilab Director, and conducted between October 1999

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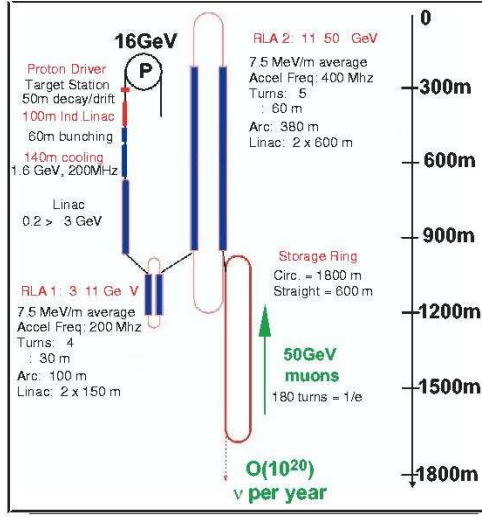


Figure 1. US Neutrino Factory schematic from design study I [4].

and April 2000. The Study I design (Fig. 1) was for a 50 GeV Neutrino Factory with the neutrino beams pointing 13° below the horizon ($L = 2900$ km). The proton source [11] consisted of a 16 GeV synchrotron producing 3 ns long bunches at 15 Hz, and providing a 1.2 MW beam (4.5×10^{14} protons per sec) on an 80 cm long carbon target located within a 20 T solenoid. The solenoid radially confines nearly all of the produced π^\pm . Downstream of the target the pions propagate down a 50 m long decay channel consisting of a 1.25 T super-conducting solenoid which confines the π^\pm and their daughter muons within a warm bore of 60 cm. At the end of the channel 95% of the initial π^\pm have decayed and, per incident proton, there are ~ 0.2 muons with energies < 500 MeV captured within the beam transport system. The muon system downstream of the decay channel is designed to produce cold muon bunches with a central momentum of 200 MeV/c. Beyond the decay channel, the muon energy spread is reduced using a 100 m long induction linac to accelerate the late low energy particles and deaccelerate the early high energy particles (phase rotation). A 2.45 m long

liquid hydrogen absorber is then used to lower the central energy of the muons. Muons with energies close to the central value are then captured within bunches using a 201 MHz RF system within a 60 m long channel. Throughout the induction linac, liquid hydrogen absorber, and bunching system the muons are confined radially using a solenoid field of a few Tesla. The buncher produces a string of bunches, captured longitudinally, but still occupying a very large transverse phase-space. Downstream of the buncher the muons are cooled transversely within a 120 m long ionization cooling channel. The phase-space occupied by the muon bunches will then fit with the acceptance of an acceleration system consisting of a linac that accelerates the muons to 3 GeV, and two recirculating linear accelerators (RLA's) that raise the muon energies to 50 GeV. The muons are then injected into a storage ring which has a circumference of 1800 m, and has two 600 m long straight sections. One third of the injected muons will decay in the downward pointing straight section. A detailed simulation of the Study I design shows that this scheme will produce about 6×10^{19} muon decays per operational year (defined as 2×10^7 seconds) in the downward pointing straight-section, which is a factor of 3 less than the initial design goal for the study. The resulting beam intensity would be sufficient for a so-called “entry-level” Neutrino Factory, but insufficient for a “high-performance” machine.

Study II, initiated by the BNL Directorate, built upon the work done during Study I and focussed on improving the Neutrino Factory design to achieve higher beam intensities. The main improvements came from using (i) a 4 MW proton source, (ii) a liquid Hg target, (iii) an improved induction linac design, and (iv) an improved cooling channel design. Detailed simulations of the Study II design predicted 2×10^{20} muon decays per operational year (redefined as 1×10^7 seconds) in the downward pointing straight-section, thus achieving the initial goal.

2.2. European Scheme

European and US Neutrino Factory designs have many similarities. However, European studies [12] (Fig. 2) have explored alternative tech-

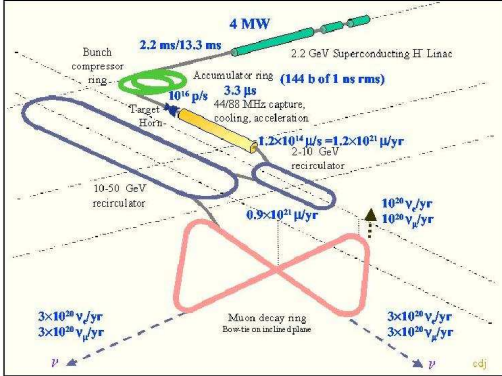


Figure 2. European Neutrino Factory scheme [12].

nologies for several subsystems: (i) The proton driver consists of a 4 MW 2.2 GeV SC linac with an accumulator ring to produce short pulses [13]. (ii) In addition to a liquid Hg jet, a water cooled Ta sphere target is being considered. (iii) The charged pions are focussed using a magnetic horn (rather than a high-field solenoid) with a 4 cm waist radius, and a peak current of 300 kA. (iv) After a 30 m drift, the muon energy spread is reduced using 44 MHz RF cavities (rather than an induction linac). (v) The ionization cooling channel uses 44 MHz and 88 MHz RF cavities, a lower frequency cavities than employed in the US scheme. (vi) A bowtie-shaped storage ring (rather than a race-track design) has been considered for the final muon ring. Simulations of the European design predict that the resulting neutrino beams will have intensities comparable to the corresponding beams from the US design. A comprehensive design study is not yet complete.

2.3. Japanese Scheme

The front end of the Japanese design (Fig. 3) consists of a 4 MW 50 GeV proton synchrotron (corresponding to an upgraded JHF complex) producing a beam incident on a target within a 12 T solenoid, followed by a large acceptance pion decay channel. Instead of manipulating and cooling the phase space occupied by the muons exiting the decay channel, very large acceptance

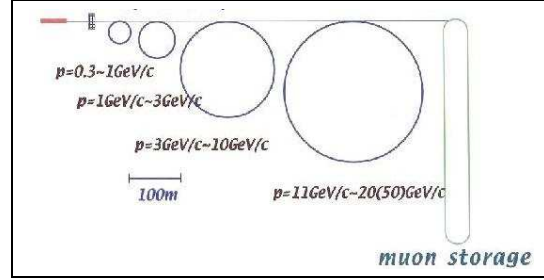


Figure 3. Japanese Neutrino Factory schematic [8].

FFAG (Fixed Field Alternating Gradient) accelerators are used to raise the beam energy before injecting into a storage ring with long straight sections. The predicted neutrino yield from this scheme seems to be comparable to the corresponding predicted yields from the US/European designs. Although the Japanese Neutrino Factory scheme might benefit from the addition of some muon cooling, in principle the use of FFAGs evades the need to cool the muons before injecting them into an accelerator. This simplification comes at the price of a more challenging accelerator, requiring complicated large aperture magnets and broad-band low frequency high gradient RF cavities. Modern design tools have made practical the task of designing the FFAG magnets, and a small proof-of-principle (POP) FFAG accelerator [14] has been built and successfully operated. A second test FFAG, designed to accelerate protons to 150 MeV, is under construction. Furthermore, with some US participation, an R&D program is underway in Japan to develop the required cavities. It is too early to conclude whether the promising Japanese Neutrino Factory scheme will lead to a more cost effective solution than the European/US-type designs. It may even be that the optimum solution consists of a combination of the two concepts, with some phase space manipulation and cooling, but using large acceptance FFAGs for the acceleration.

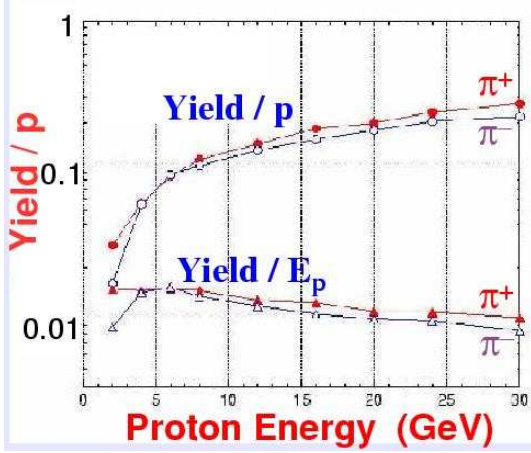


Figure 4. MARS predictions [4]. The number of $\pi^+ + \mu^+$ (filled symbols) and $\pi^- + \mu^-$ (open symbols) within an energy interval $30 \text{ MeV} < E < 230 \text{ MeV}$ is shown 9 m downstream of an 80 cm long 0.75 cm radius carbon target within a 20 T solenoid, and tilted 50 mrad with respect to the solenoid axis. Triangles show the yields divided by the primary proton energy.

3. Pion production & Target R&D

To produce a sufficient number of π^\pm , all Neutrino Factory schemes begin with a MW-scale proton driver. Figure 4 shows predicted yields for π^\pm captured within a decay channel downstream of a Neutrino Factory target system. Over a broad interval of beam energies, at fixed beam power the yields are approximately independent of beam energy. The E910 experiment at BNL [15] has recently measured π^\pm yields for several targets and different incident proton beam energies. Some of the results are shown in Fig. 5. The measurements are in fair agreement with MARS calculations [15]. The pion yields peak in the region 300 - 500 MeV/c. Hence, Neutrino Factory designs tend to have π^\pm collection systems optimized to capture particles with momenta in this range. In the next few years we can anticipate further particle production measurements from the HARP experiment [16] at CERN, and the Fermilab E907 experiment [17].

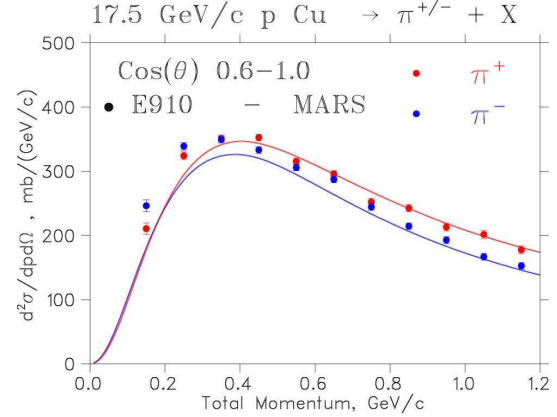


Figure 5. Pion production measurements from the BNL E910 experiment, compared with MARS predictions [15].

Entry-Level Neutrino Factories providing a few $\times 10^{19}$ useful muon decays per year require proton beams with beam powers of $\sim 1 \text{ MW}$, and short proton bunches, typically a few ns long. It is believed that carbon targets can operate with these beam parameters. This has been tested at BNL by the E951 Collaboration [18]. Two different types of carbon rod were exposed to the AGS beam and strain gauge data taken. The beam induced longitudinal pressure waves and transverse reflections were both measured. The strains in the two types of rod differed by an order of magnitude, the most promising rod being made from an anisotropic carbon-carbon composite.

High performance Neutrino Factories providing $O(10^{20})$ useful muon decays per year require $\sim 4 \text{ MW}$ proton beams. Solid targets will melt unless very efficient cooling strategies can be developed. Rotating metal bands [19] and water cooled Ta spheres [20] are being considered, but the presently favored solution is to avoid problems with target melting and integrity by using a liquid Hg jet. In the US and Japanese schemes the target is in a high-field solenoid. Hence, the main R&D issues are (i) can a Hg jet be injected within a high-field solenoid without magneto-hydrodynamic effects disrupting the jet, (ii) after the jet has been destroyed by one

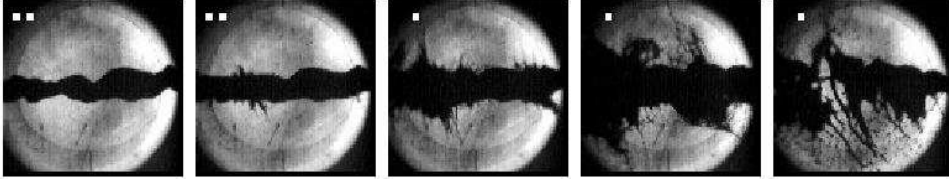


Figure 8. BNL E951 results [19]. The sequence of pictures shows the Hg jet at the time of impact ($t=0$) of the AGS beam, and at $t = 0.75$ ms, 2 ms, 7 ms, and 18 ms. Time increases from left to right.

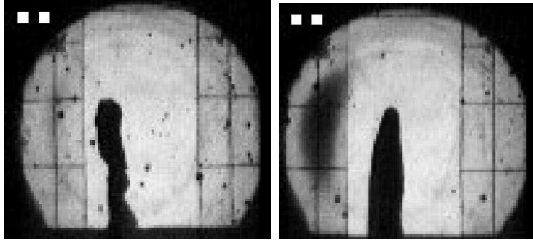


Figure 6. CERN-Grenoble tests in which a liquid Hg jet is injected into a solenoid providing 0 field (top picture) and 13 T (bottom picture) [13].

proton pulse will it re-establish itself before the next pulse, and (iii) can the disrupted jet be safely contained within the target system. To address these questions, R&D has begun at CERN and BNL. Photographs of a liquid Hg jet injected into a 13 T solenoid at Grenoble are shown in Fig. 6. The solenoid field seems to damp surface tension waves, improving the jet characteristics. The BNL E951 liquid Hg jet setup [18] in the 24 GeV AGS beam is shown in Fig. 7. Figure 8 shows a sequence of pictures of the 1 cm diameter Hg jet taken by a high speed camera from the time of impact of 4×10^{12} protons in a 150 ns long pulse from the AGS. Jet dispersal is delayed for about $40\mu\text{s}$. It takes several ms before the jet, which has an initial velocity of 2.5 m/sec, is disrupted. The velocity of the out-flying Hg filaments appears to scale with beam intensity, and is ~ 10 m/sec for a deposited energy of 25 J/g. These velocities are modest, implying that the disrupted jet can be easily contained within the target system. Furthermore, the Hg jet dispersal is mostly in the transverse direction, and after disruption it has

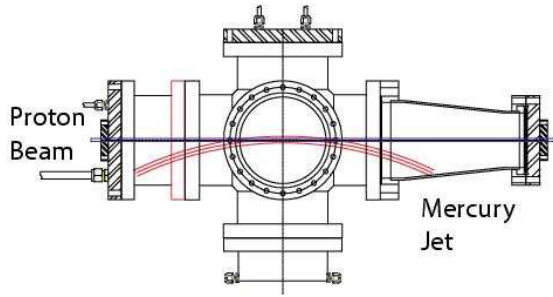


Figure 7. Schematic of the E951 system to test a Hg jet in the BNL AGS beam [19].

been found that the jet quickly re-establishes itself. However, high performance Neutrino Factories will require Hg jets with higher velocities (~ 20 m/sec). The next steps in the E951 R&D require beam tests with a factor of a few higher beam intensities, and finally beam tests in which the Hg jet is injected into a 20 T solenoid.

4. Muon Cooling R&D

Before the muons can be accelerated the transverse phase-space they occupy must be reduced so that the muon beam fits within the acceptance of an accelerator. This means the muons must be “cooled” by at least a factor of a few in each transverse plane, and this must be done fast, before the muons decay. Stochastic- and electron-cooling are too slow. It is proposed to use a new cooling technique, namely “ionization cooling” [10]. In an ionization cooling channel the muons pass through an absorber in which they

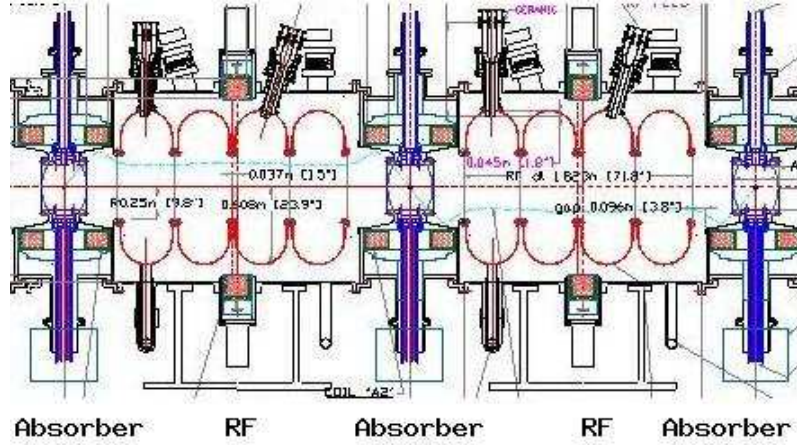


Figure 9. SFOFO cooling channel design [5]. A 5.5 m long section is shown, consisting of two 200 MHz four-cell cavities interleaved with three liquid hydrogen absorbers.

lose transverse- and longitudinal-momentum by dE/dx losses. The longitudinal momentum is then replaced using an RF cavity, and the process is repeated many times, reducing the transverse momenta. This cooling process will compete with transverse heating due to Coulomb scattering. To minimize the effects of scattering we chose low- Z absorbers placed in the cooling channel lattice at positions of low- β_{\perp} so that the typical radial focusing angle is large. If the focusing angle is much larger than the average scattering angle then scattering will not have much impact on the cooling process. In the US, detailed simulation studies have identified two promising linear cooling channel designs: “SFOFO” and “DFLIP”.

In the SFOFO lattice the absorbers are placed at low- β_{\perp} locations within high-field solenoids. The field rapidly decreases from a maximum to zero at the absorber center, and then increases to a maximum again with the axial field direction reversed. Figure 9 shows the design for a 5.5 m long section of the ~ 100 m long cooling channel. The section shown has 30 cm long absorbers with a radius of 15 cm, within a system of solenoids with a peak axial field of 3.5 T. Towards the end of the cooling channel the maximum field is higher (5 T) and the lattice period shorter (3.3 m). The RF cavities operate at 201 MHz and provide a peak gradient of 17 MV/m. Detailed simulations pre-

dict that the SFOFO channel increases the number of muons within the accelerator acceptance by a factor of 3-5 (depending on whether a large- or very-large acceptance accelerator is used).

In the DFLIP lattice the solenoid field remains constant over large sections of the channel, reversing direction only twice. In the early part of the channel the muons lose mechanical angular momentum until they are propagating parallel to the axis. After the first field flip the muons have, once again, mechanical angular momentum, and hence move along helical trajectories with Lamour centers along the solenoid axis. Further cooling removes the mechanical angular momentum, shrinking the beam size in the transverse directions. The field in the early part of the channel is 3 T, increasing to 7 T for the last part. Detailed simulations show the performances of the DFLIP and SFOFO channels are comparable.

Recently there has been considerable progress in the design of cooling channels configured in a ring, and incorporating wedge-shaped absorbers at locations where higher energy muons pass through the thick end of the wedge. This cools both longitudinal and transverse phase space. The simulations, which predict ring coolers have wonderful performance, do not yet incorporate realistic absorbers or detailed injection and extraction schemes. It remains to be seen if realistic

ring coolers will result in greatly improved performance and significant cost savings compared to the present baseline cooling channels.

4.1. MUCOOL R&D

Muon cooling channel design and development is being pursued within the US by the MUCOOL collaboration [21]. The MUCOOL mission includes bench-testing all cooling channel components and beam-testing a cooling channel section. The main component issues that must be addressed are (i) can sufficiently high gradient RF cavities be built and operated in the appropriate magnetic field and radiation environment, and (ii) can liquid hydrogen absorbers with thin enough windows be built so that the dE/dx heating can be safely removed. The MUCOOL collaboration has embarked on a design-, prototyping-, and testing-program that addresses these questions.

RF Cavity Development

Cooling channel studies initially began with Muon Collider cooling channel designs using 805 MHz cavities operating in a 5T solenoid, and providing a peak gradient on axis of ~ 30 MV/m. This deep potential well is needed to keep the muons bunched as they propagate down the channel. This requirement led to two cavity concepts: (a) an open cell design, and (b) a design in which the penetrating nature of the muons is exploited by closing the RF aperture with a thin conducting Be window (at fixed peak power this doubles the gradient on axis). The MUCOOL collaboration has pursued an aggressive 805 MHz cavity development program. A 12 MW high power test facility has been built and operated at Fermilab (Lab G), enabling 805 MHz cavities to be tested within a 5T solenoid. The main results to date are: (i) An open cell cavity suitable for a muon cooling channel has been designed, an aluminum model built and measured, and a prototype copper cavity built, tuned, and tested at full power (Fig. 10). Dark current produced by the cavity has been identified as an important R&D issue [22]. (ii) A Be foil cavity has been designed at LBNL, a low power test cavity built and measured, and foil deflection studies made [23] to ensure the cavity does not detune when the foil is



Figure 10. High power 805 MHz cavity test in the MUCOOL Lab G test area, Fermilab [25].

subject to RF heating. The foil deflection is reasonably well understood for small displacements. A high power copper cavity with thick Be windows has been built at LBNL and the University of Mississippi, and tested at full power at Lab G. Magnetic field studies will start soon.

The cooling channel designs developed in the US Neutrino Factory studies require 201 MHz RF cavities providing ~ 17 MV/m on axis. Preliminary cavity designs have been made. There are two concepts, both of which close the cavity aperture. The options are to use (a) a thin Be foil, exploiting the work done for the 805 MHz cavity, or (b) use a grid of hollow conducting tubes. Preliminary mechanical tests for both the grid and foil concepts are planned. The 805 MHz R&D program will be extended so that windows and grids can be tested at high power. The 805 MHz program will also enable us to obtain a better understanding of how to build low dark-current NCRF cavities, providing critical guidance for the 201 MHz cavity prototype that we hope to build and test in the next couple of years.

Absorber Development

The cooling channel liquid hydrogen absorbers must have very thin windows to minimize multiple scattering, and must tolerate heating of

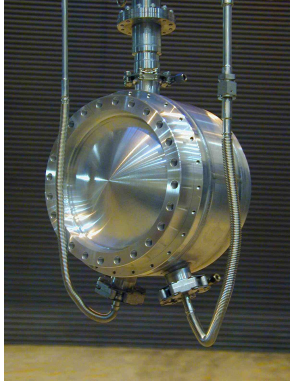


Figure 11. KEK prototype absorber. The liquid hydrogen is to be mixed by convection and cooled with a local heat exchanger.

O(100 W) from the ionization energy deposited by the traversing muons. Typical absorber parameters are: 35 cm long, 18 cm radius, with $360\text{ }\mu\text{m}$ thick Al windows, operated at 1.2 atm. To adequately remove the heat from the LH_2 requires good transverse mixing. There are two absorber designs that are being pursued [24]: (i) Forced flow design. The LH_2 is injected into the absorber volume through nozzles, and cooled using an external loop and heat exchanger. (ii) Convection design. Convection is driven by a heater at the bottom of the absorber volume, and heat removed by a heat exchanger on the outer surface of the absorber. A forced flow absorber prototype is being designed at the Illinois Institute of Technology (IIT) and will be constructed in the coming year. A convection prototype, designed by IIT, KEK, and the University of Osaka, is being constructed in Japan (Fig. 11). Both absorbers will be tested at Fermilab.

Prototype 15 cm radius aluminum absorber windows have been made at the University of Mississippi, and pressure tested at Northern Illinois University [24]. The window thickness and profile were measured at FNAL and found to be within 5% of the nominal envelope. Strain gauge and photogrammetric measurements were made as a function of pressure, and the results compared with FEA predictions. The last window

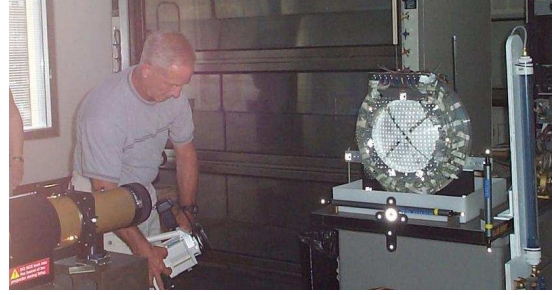


Figure 12. Absorber window test, showing an array of dots projected onto the window for photogrammetric measurements of its shape as it deforms under pressure [27].

was tested at LN_2 temperature. The FEA predictions give an excellent description of the deformation with pressure and the rupture pressure.

4.2. European Cooling R&D Program

The European cooling channel design [25] is similar to the US design, but is based on 44 MHz and 88 MHz cavities [26] rather than 201 MHz cavities. To minimize the radii of the solenoids used to confine the muons the cavities have been designed to wrap around the solenoids. The initial transverse cooling is performed using 44 MHz cavities with four 1 m long RF cells between each 24 cm long LH_2 absorber. The beam is then accelerated from 200 MeV to 300 MeV, and the cooling is continued using 88 MHz cavities with eight 0.5 m long cells between each 40 cm long LH_2 absorber. Simulations of the channel performance with detailed field-maps have not yet been made. However, simulations using simpler field maps yield promising results: the effect of the channel is to increase the number of muons within the acceptance of the subsequent accelerating system by a factor of about 20. Whether or not the predicted increased yield is significantly degraded when full simulations are performed remains to be seen. In the meantime, a prototype 88 MHz cavity is being prepared at CERN for high power tests within the coming year.

4.3. Cooling Experiments

A sequence of muon cooling-related experiments is being planned. The first, the MUSCAT experiment, is already under way at TRIUMF. The second, the MUCOOL Component Test Experiment, is under construction at the Fermilab Linac. The third, an International Cooling Experiment [27], is in the planning stage.

The goal of the MUSCAT experiment is the precise measurement of low energy (130, 150, and 180 MeV/c) muon scattering in a variety of materials that might be used in a cooling channel. In a second phase MUSCAT will measure straggling. Scattering measurements for Li, Be, C, Al, CH₂, and Fe have already been made.

A MUCOOL test area located at the end of the Fermilab 400 MeV Linac is under construction. The project is being pursued in two phases. In Phase 1 a LH₂ absorber test facility is being built, which will enable the first prototype absorbers to be filled. In Phase 2 a linac beam will be brought to the absorber area, and the 5T solenoid will be moved from Lab G so that the absorber can be tested in a magnet whilst exposed to a proton beam. The beam intensity and spot size will be designed to mimic the total ionization energy deposition and profile corresponding to the passage of $10^{12} - 10^{13}$ muons propagating within a cooling channel. In addition, 201 MHz RF power will be piped to the test area from a nearby test-stand, enabling high-power tests to be made of a prototype 201 MHz cooling channel cavity.

A Europe-Japan-US International Cooling Experiment (MICE) is currently being planned [27]. The goals are to (i) place a cooling channel section in a muon beam, and (ii) demonstrate our ability to precisely simulate the passage of muons confined within a periodic lattice as they pass through LH₂ absorbers and high-gradient RF cavities. In the envisioned experiment muons are measured one at a time at the input and output of the cooling section, and the precise response of the muons to the cooling section is determined. The main challenge to the design of this type of experiment arises from the prolific X-ray and dark current environment created by the RF cavities. This is currently under study at Lab G and elsewhere. The MICE Collaboration has been invited

to submit a full proposal to the Rutherford Lab at the end of 2002.

5. Muon Acceleration

The acceleration system has been identified as one of the cost drivers for a Neutrino Factory. In the US and European schemes the main acceleration systems use SC cavities. The US scheme uses 201 MHz SCRF delivering gradients of 15 MV/m with $Q \sim 5 \times 10^9$. Note that 201 MHz is a relatively low frequency and the cavities are therefore large. The associated R&D issues are related to microphonics, fabrication and cleaning techniques and, because of the large stored energy, quench protection. Furthermore, the cavities must tolerate whatever stray magnetic fields they see within the accelerating lattice. To address these issues a 201 MHz SC cavity has been constructed at CERN and sent to Cornell for high-power testing.

6. Summary and Prospects

Muon sources capable of delivering $O(10^{20})$ muons per year seem feasible, and would enable Neutrino Factories, and perhaps eventually Muon Colliders, to be built. Neutrino Factory designs have been developed in Europe, Japan, and the US, and a healthy R&D program is underway. The most challenging R&D questions are associated with targets for MW-scale proton beams, and the development of an ionization cooling channel. With the present level of support, we can expect much progress in Neutrino Factory R&D over the next few years. However, the news is not all good. The future level of support is uncertain. I believe a significant increase (factor of two ?) will be needed, sustained over a handful of years, if we are ever to arrive at a "Technical Design Report". In addition, there must be good international collaboration to enable the most promising design to be eventually chosen. There is already a healthy dialogue between the European, Japanese, and US R&D teams, and some cross-participation in the various R&D programs. Finally, it should be noted that Neutrino Factory R&D is being pursued by engineers, ac-

celerator physicists, and particle physicists from Laboratories and Universities in Europe, Japan and the US. There are a broad range of interesting sub-projects to be pursued. With adequate support, the prospects seem bright.

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